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Use of the attainable region method to simulate a full-scale ball mill with a realistic transport model

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ABSTRACT

Optimisation and better control of milling circuits require extensive modelling of milling data. This paper extends the enquiry to the use of the attainable region (AR) technique to determine the optimal residence time of ore in a ball mill. It also evaluates the energy requirements of the mill at the set residence time to maximise the production of the desired size range which enables maximum recovery of platinum group minerals (PGM) during the flotation stage.

With these purposes in mind, the breakage function and the scaled-up selection function parameters were used to simulate the operating conditions required by an industrial ball mill and the power requirements were predicted using the Morrell power model. This allowed the application of the AR methodology to be extended to a full-scale ball mill. Then a link was established between residence time to mill product specifications for a given feed size.

The findings showed that the residence time required by a full-scale mill falls between those at which the fully mixed and the plug flow mills operate. The results also showed that operating the ball mill at a lower mill speed and a higher ball filling saves energy. Mill speed was again found to be a key operational factor for controlling the retention time of particles inside the mill. This yielded valuable insight for the importance of optimally controlling both the residence time of the material inside the mill and the amount of energy required to maximise the desired size range, in this case −75 + 9 μm.

1. Introduction

Previous studies have shown that joining the scale-up equation with description of the distribution of residence time in the mill enables successful construction of simulation model for the steady-state continuous operation (Austin et al., 1984).

Mulenga and Chimwani (2013) demonstrated that it is possible to optimise the mean residence time τ while maximising a predetermined particle size range (that is to determine the shortest residence time needed to produce the maximum amount of the desired particle size range) for two mill transport models; namely, the plug flow and fully mixed mills, using the model proposed by Austin et al. (1984) that is expressed as follows:

$$p_i = w_i(\tau) = \sum_{j=1}^{i} d_{i,j} f_j, \quad \text{with } n \geq i \geq j \geq 1, \tag{1}$$

where $w_i(\tau)$ is the final product; f_i is the initial feed; $d_{i,j}$ is the fraction of feed size j transferred to size i in the product via the repeated breakage steps over time τ.

The RTD of a full-scale mill, which is intermediary to the two extremes was successfully treated as the equivalent of one large fully mixed reactor (τ_1) followed by two equal small fully mixed reactors (τ_2) with no post-classification (Austin et al., 1984). Later, Makokha et al. (2011) also treated it as such but added the dead time (τ_d) to the series of tanks and described the dynamics for the dead time zone using the Dirac plug flow function.

The set of $d_{i,j}$ values for the RTD model represents the mill transfer function between feed and product and is given by:

$$d_{i,j} = \begin{cases} \dfrac{e^{(-S_j \tau_d)}}{(1+S_j.\tau_1)(1+S_j.\tau_2)^2}, & i = j \\ \displaystyle\sum_{k=j}^{i-1} c_{i,k} \cdot c_{j,k} \cdot \left(\frac{e^{(-S_k \tau_d)}}{(1+S_k.\tau_1)(1+S_k.\tau_2)^2} - \frac{e^{(-S_i \tau_d)}}{(1+S_i.\tau_1)(1+S_i.\tau_2)^2} \right), & i > j \end{cases}, \tag{2}$$

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$$c_{i,j} = \begin{cases} -\sum_{k=i}^{j-1} c_{i,k} \cdot c_{j,k}, & i < j \\ 1, & i = j \\ \frac{1}{S_i - S_j} \cdot \sum_{k=j}^{i-1} S_k \cdot b_{i,k} \cdot c_{k,j}, & i > j \end{cases} \quad (3)$$

$c_{i,j}$ is the transformation matrix used for the generation of the transfer function matrix $d_{i,j}$ which describes the breakage process within the population balance framework.

A schematic representation of the full mill using the RTD model developed by Makokha (2011) is shown in Fig. 1. The equations for the three partial residence times (that is, τ_d, τ_2 and τ_1) are given below (Makokha, 2011):

$$\begin{cases} \tau_1 = 0.841\tau - 2.531 \\ \tau_2 = 0.051\tau + 1.377 \\ \tau_d = 0.046\tau - 0.222 \end{cases} \quad (4)$$

where τ represents the total residence time of the full-scale mill.

The same methodology centred on the AR technique to optimise mean residence time while maximising a pre-determined particle size range as proposed by Mulenga and Chimwani (2013) is used in this work.

Just to shed more light on the AR technique. It is a flexible tool used for graphical analysis of data, which overlooks milling parameters but instead focuses on the fundamental breakage process and determines the set of all achievable size distributions under the process conditions, hence providing the designer with the best pathway to achieving a specific objective function from the system feed. The more detailed examples of its use given below start with the demonstration by Metzger et al. (2009) that from the grinding of a single charge constituting narrow-size class feed for different grinding durations, it is possible to generate product size distributions for those grinding times and to develop grinding profiles for each size class produced. Fig. 2 below is an illustration of how experimental data can be represented for both cases. The grinding profiles can then be grouped into mass fractions m_1, m_2 and m_3, where m_1 is termed the feed size class, m_2 the middling size class and m_3 the fines size class. The margins of the mass fractions are dependent on the objective function to be achieved. For example, if we consider m_1 to consist of size class 1 and 2, m_2 to be made of size class 3 and 5 while size class 6 constitutes m_3, we can clearly define our objective function.

Fig. 2 illustrates the mass fractions of m_1, m_2 and m_3. If the objective is to maximise the production of the middling (m_2), then from the AR analysis illustrated here, we can interpret the graph to determine the optimal grinding time. We can then extend this analysis to compare the discrete maxima of m_2 obtained under different specified operating conditions. An example of different maxima of m_2 obtained with dissimilar media charges (J) at a single speed is illustrated in Fig. 3.

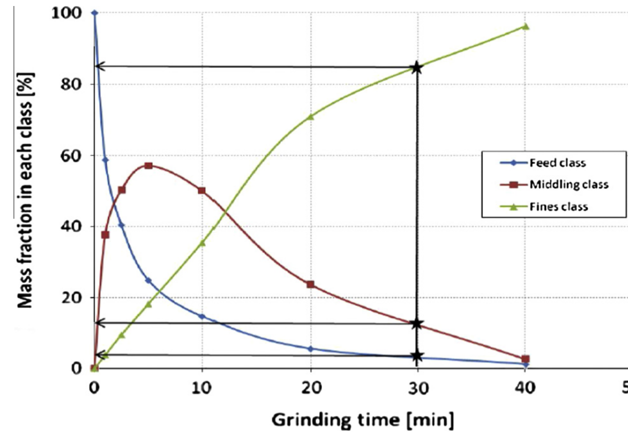

Fig. 2. Grinding kinetics as plotted for the three size classes m_1, m_2 and m_3 (Katubilwa et al., 2011).

Now that mass fractions at different grinding times have been clearly explained, the next step is to present the data in a final AR format. Fig. 3 shows how particle size distributions (PSD) can be connected with grinding time. In this plot, the boundary curve describes the processes used, and can be interpreted in terms of pieces of equipment (implicitly identifying the equipment required for best performance). The turning point of the curve isolates an optimum solution when the objective is to maximise the mass in size class 2 (m_2). This solves the optimisation problem, and provides the process control policy needed to achieve that objective.

In this research work, the residence time optimisation is expanded from the simple transport models to a more realistic approach, and the analytical methodology developed in the previous work by Mulenga and Chimwani (2013) is applied. The residence time distribution (RTD) model comprises a dead zone, two small fully mixed tanks and one large fully mixed reactor (Makokha et al., 2011). The result flow pattern through these series of tanks describes very well the residence time distribution of slurry in the mill as a function of ball filling, slurry filling, and feed flow-rate.

The population balance model (PBM) framework and the more realistic transportation model made it possible to predict the evolution of the mill product size and the amount of energy used in the process. Different mill conditions were explored by simulation and the data generated were analysed using the AR scheme. Practical residence time boundaries were determined for the optimal production of floatable material. It should be noted that no exit classification was considered in the mill model.

2. Research methodology

In this research, the simulations were built upon the research that was undertaken earlier by Chimwani et al. (2012) in which

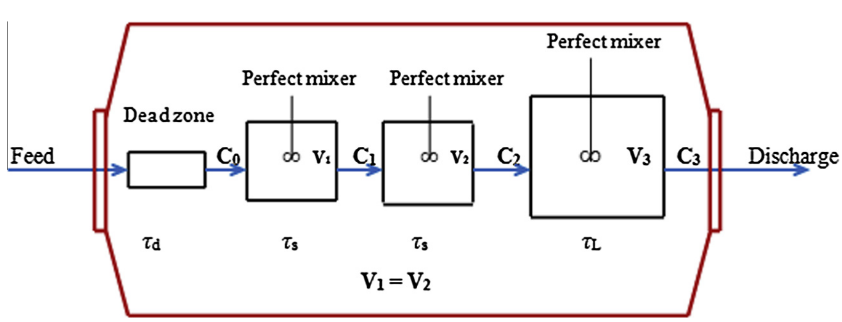

Fig. 1. Schematic representation of the tanks in series model with dead time (after Makokha et al., 2011).